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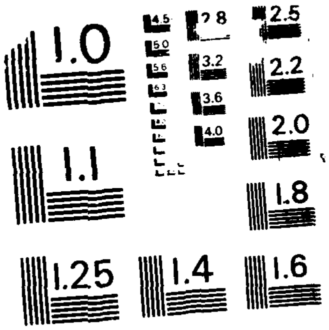
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THE NEW UCSB COMPACT FAR-INFRARED FEL †

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ABSTRACT

A 2 mega-volt electrostatic accelerator is being acquired by the FEL development group at the University of California, Santa Barbara (UCSB). This machine is being designed to provide an exceptionally low emittance electron beam suitable for a wide range of FEL related experiments. Foremost among these will be development of a compact submillimeter FEL employing "next generation" electrostatic accelerator FEL concepts. It is expected that this machine will serve as prototype for a new generation of FELs all based on commercially available electrostatic accelerators ranging in voltage from .5 to 25 Megavolts. Generation of radiation from millimeter to visible wavelengths at power levels from kilowatts to megawatts from relatively cheap and compact machines is anticipated. Components for the 2 MV accelerator have been ordered and High voltage tests are expected to begin early in 1988.

INTRODUCTION

An Electrostatic accelerator driven FEL has been in operation at UCSB since 1984 and is currently supplying submillimeter radiation to an associated users' facility. Original doubts about the suitability of electrostatic accelerators as FEL beam sources were addressed during the course of the UCSB development program. Successes included production of a high-quality ampere-level electron beam, transport of that beam through an accelerator tube originally designed for low current ion beams, deceleration and capture of that beam at 95 % recirculation level after transport through the FEL undulator and finally, demonstration of laser oscillation. Additionally, a novel hybrid waveguide resonator was developed with sufficiently low loss to permit submillimeter lasing. The success of the UCSB FEL has demonstrated that not only is an electrostatic accelerator suitable, but actually desirable as a beam source.

In comparison with other beam sources, the electrostatic accelerator is relatively compact, cheap, reliable, and efficient and it has long been a goal to extend these attributes to the complete FEL. Extension of operating wavelength range and power levels is also desired. We believe achievement of these goals is possible through a series of "next generation" concepts including location of the resonator within the accelerator terminal operated at positive potential, the electron gun and collector located outside of the accelerator, and the use of a "micro-undulator" [1]. These, along with the original UCSB FEL concepts, define an evolutionary path for future development.

A program to implement and develop these concepts is now underway at UCSB. Initially a compact submillimeter FEL will be built using a 2 MV test accelerator. This will serve as a prototype for higher voltage shorter wavelength machines of the future as well as providing the UCSB users' facility with a second radiation source. With development of this machine, a number of significant problems will be addressed including handling and diagnostics of very small high current density electron beams and transport of rapidly diffracting long wavelength optical beams across a high voltage gap.

"NEXT GENERATION" CONCEPTS

A number of extensions to the UCSB FEL concept have been identified that will permit construction of very compact submillimeter machines or larger high voltage machines capable of producing visible radiation at megawatt power levels, all based on commercially available accelerators. We refer to these (illustrated in Fig. 1) as "next generation" concepts. With the "present generation" UCSB FEL, the electron beam is generated within a negative high voltage terminal, accelerated, and then transported around the laboratory through the FEL undulator, and finally returned to the accelerator for deceleration and collection. The new concepts include the use of a positive terminal potential with the undulator and resonator located inside and the electron gun and collector outside at ground potential. Sensitive electronics such as the gun's pulser are then located outside the high voltage environment for improved reliability. The relatively short direct inline electron path will result in lower losses and minimal x-ray production. A smaller number of beam optic components will also result in less beam degradation. Recirculation levels are expected to be as high as 99%. The use of a micro-undulator reduces overall size and the positive terminal potential permits higher fields within the insulating gas and consequently even smaller overall size.

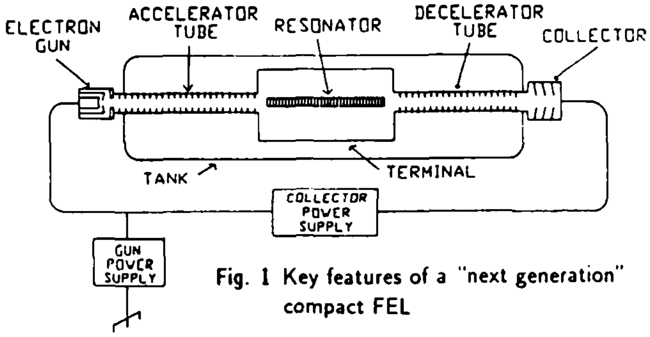

Fig. 1 Key features of a "next generation" compact FEL

The advisability of placing delicate optical components within the accelerator has been questioned but the present UCSB FEL has been in operation for about three years during which time its resonator and undulator have required essentially no attention. In fact the resonator mirror steering servos were long ago disconnected. This is not unreasonable considering the waveguide configuration, the relatively long wavelengths, and the quasi-DC electron beam pulse which makes critical resonator length tuning unnecessary. On the other hand, the electron gun, collector, and their associated electronics have required frequent attention mostly due to damage from sparking.

Our plan is to employ all these concepts within the new UCSB compact FEL and show that they represent an evolutionary path for future electrostatic accelerator based FEL development.

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ACCELERATOR

The most important characteristic of an electrostatic accelerator is the static DC electric fields it produces. The unique properties the UCSB FEL are directly attributable to this nearly ideal characteristics of an electron beam generated with a DC electrostatic field. First, the lack of a temporal micro-structure characteristic of RF accelerators such as linacs, microtrons, and storage rings permits extremely narrow linewidth and very long coherence length operation [2]. Typically, linewidth of an RF accelerator based FEL is Fourier transform limited to a few tenths of a percent by a several picosecond electron microstructure. Also, for certain applications, non-linear behavior or material damage problems are aggravated by the extremely high peak powers associated with this microstructure. Second, very good beam quality is maintained by the use of uniform electrostatic fields during acceleration while large alternating field gradients within RF cavities can cause serious degradation. The bunching properties of RF machines are also responsible for introduction of a relatively large energy spread that is totally absent in electrostatically generated beams. Third, the ease with which recirculation is implemented in an electrostatic accelerator leads to very high efficiency FEL operation. No RF machine can duplicate the nearly perfect efficiency with which such a beam can be decelerated and captured using DC electrostatic fields.

The present UCSB FEL is based on a 6 Megavolt accelerator supplied by National Electrostatics Corp. (NEC)[3]. It is important to note that such accelerators are commercially available from NEC at voltages between 1 and 25 MV and possibly higher with further technical development. These are relatively compact self contained machines that have a well established reputation for reliability over many years of service in ion beam research.

The UCSB FEL development group presently has on order with NEC components for a 2 MV horizontal double ended accelerator. This machine is illustrated in Fig. 2 along with the compact submillimeter FEL components. The machine is intended to be a general test accelerator and will be used for many FEL related experiments. Experimental work will be facilitated by features such as rapid insulating gas transfer, a hydraulic fast acting door, and a capacious terminal. The machine is scheduled to be completed in February, 1988 with high voltage testing beginning in March.

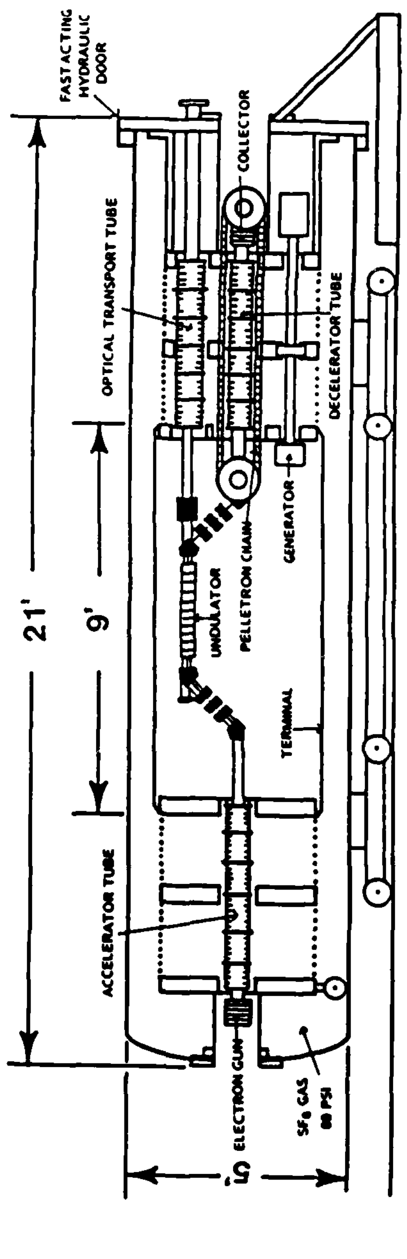

Fig. 2 Illustration of compact FEL built into the 2 MV test accelerator

COMPACT FEL

Parameters of the compact submillimeter FEL are listed in Table 1. These are calculated mostly from single particle theory with numerical methods used where appropriate. Many parameter tradeoffs are possible and choices were made here to minimize risk while still providing useful radiation and most importantly, to address problems consistent with the nature of this machine as a prototype of future FELs.

TABLE 1 Parameters of the 2 MV compact FEL

Energy	2.0 MEV	L_r	.95 m
I	2.0 A	h_y	2.0 mm
γ	4.91	Mirrors	Cylindrical
β_z	.979057	R_m	.56 m
β_t	.005646	W_m	2 cm
λ_0	4 mm	ω_0	2.38 mm
λ	86 μm	A_{mode}	.043 cm^2
Undulator	Micro	G_{ss}	24 %
Polarization	Linear	l_{total}	12 %
B_r	10.5 KG	l_d	0.3 %
B_{y0}	1050 Gauss	l_r	1.0 %
gap	2.3 mm	Coupling	Hole
K	.02774	dia.	.7 mm
L_u	.8 m	cpl	4.6 %
N_{per}	200	P_{sat}	8.9 KW
Resonator	H-Waveguide	P_{out}	3.5 KW

The most important parameters in this type of FEL design are small signal gain which must be sufficient to promote oscillation and homogeneously broadened bandwidth which sets limits on the exchange of energy between the electron beam and optical mode. The relationship between small signal gain and key FEL parameters is

$$G_{ss} \propto \lambda_0 B^2 I L^3 A^{-1} \gamma^{-3}$$

By comparison with the present UCSB FEL, a large loss of gain is expected from the much shorter undulator length and period. This is completely compensated by the very much smaller mode area and lower γ. The concept of homogeneously broadened bandwidth has been useful, since the inception of lasers, in describing energy exchange mechanisms and for the FEL, as for conventional lasers, is determined by spontaneous emission characteristics which are in turn determined by temporal coherence limits. For the FEL, the limit is simply the time duration of the undulations executed by the electron in its passage through the undulator, $t = L/\beta c$.

An upper limit to homogeneously broadened bandwidth is simply the Fourier transform of this finite number of wiggles,

$$F(\omega) = \frac{1}{\sqrt{2\pi}} \int_{-T}^{T} \frac{1}{2T} e^{-i\omega t} dt$$

defining a power spectral full width at half maximum (FWHM) of

$$\frac{\delta\omega}{\omega} = \frac{\sqrt{2}}{\pi N}$$

where N is the number of periods of length λ_0. For the conditions of Table 1, a fractional bandwidth of 2.3×10^{-3} results. This bandwidth determines the maximum energy exchange possible between an electron and the radiation field, and therefore, sets an upper limit to small signal gain saturation and thus maximum laser output under ideal conditions. Equally important, it sets limits on electron beam dimensions, energy spread, and emittance as well as undulator field homogeneity.

UNDULATOR

An important requirement of the next generation electrostatic accelerator based FELs is the generation of undulator periods in the range of 3 to 6 millimeters. Most FELs, including the present UCSB FEL use periods ranging from 2 to 20 centimeters. Difficulties encountered in construction of the UCSB undulator at 3.6 cm [4] led us to believe that construction of undulators from discrete magnets with periods shorter than 1 cm would be impractical. We therefore identified a new magnetic structure referred to as a "micro-undulator" (Fig 3a)[1]. A plot of the fields produced by this structure is shown in Fig. 3b. The structure consists of grooves ground onto the faces of relatively large homogeneously magnetized blocks of Samarium-Cobalt material. Research into techniques needed to correct field nonuniformities is presently underway at UCSB.

a

b

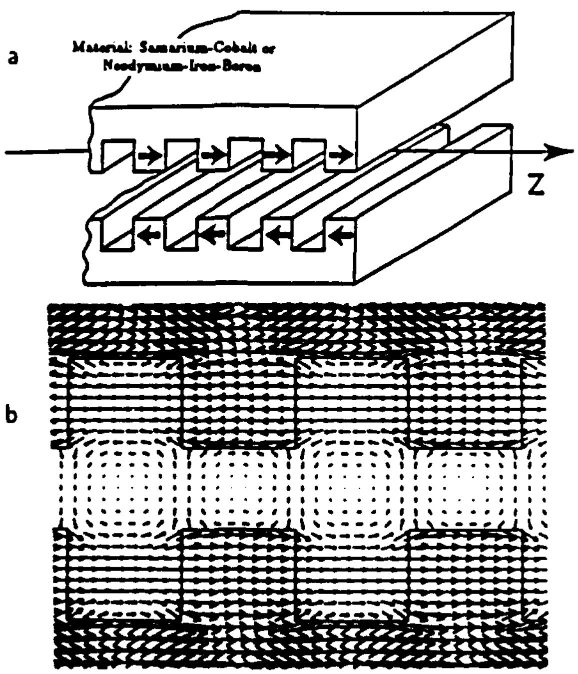

Fig. 3 a) Structure of the "micro-undulator" consisting of grooves ground in homogeneously magnetized blocks of material b) Magnetic field plot from two-dimensional solution of Poison's equation in $y - z$ plane

The recent availability of Neodymium-Iron-Boron material with its superior mechanical properties has perhaps made millimeter period undulators constructed from discreet magnets practical. The "hybrid" configuration [5] would be particularly attractive. A decision whether to use the "micro" or "hybrid" configuration for the new 2 MV submillimeter FEL has not as yet been made and will depend on the outcome of research currently underway.

ELECTRON BEAM OPTICS

As indicated in Fig. 2, the electron gun and collector are located outside and at opposite ends of the accelerator pressure vessel. This results in a short electron beam path that can be expected to generate relatively small beam degradation, current loss, and x-ray production. A nominal 2 Amp beam current was chosen to take advantage of the present UCSB low current guns (see Fig. 4) which are becoming surplus with the present machine's conversion to 20 Amps. These guns provide a very high quality beam with nearly thermally limited emittance [6] and have given outstanding service for several years. A preliminary design of a new single stage collector is shown in Fig. 5a with trajectory plots in fig 5b. The salient features are off-axis collection with secondary suppression and a strait-through optical path in anticipation of future laser-driven gun experiments.

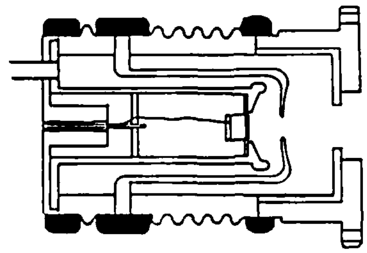

Fig. 4 Illustration of the UCSB 2 amp electron gun to be used in the compact FEL

a

b

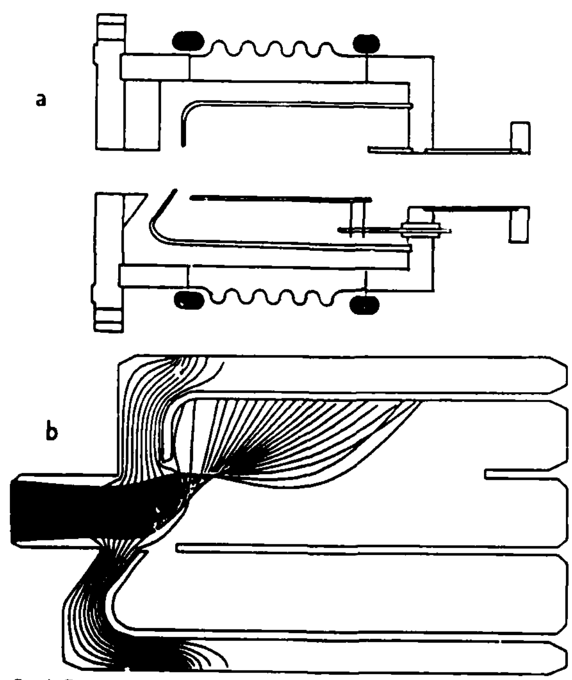

Fig. 5 a) Preliminary design of a single stage off-axis collector with secondary suppression for the compact FEL b) Trajectory plot of the collector

As with most FELs, provision for injection of the electron beam into, and separation from, the optical mode is necessary. Here this is accomplished by two fully achromatic offset sections each consisting of two 45 degree dipoles and two quadrupoles. The two quadrupoles are strongly focussing in the bending plane and cause symmetrical dispersion cancellation. A third quadrupole in the center provides non-bending plane beam size control. Beam envelope and dispersion characteristics are plotted in Fig. 6. It should be noted that other configurations such as the chicane are suitable and might provide a more compact system at the expense of additional dipoles.

BEAM DIAGNOSTICS

To appropriately match the optical mode, the electron beam form within the resonator will be highly eccentric ellipse with semi-minor and major axes of .5 mm and 5 mm respectively as shown In Fig. 6. The resulting very high current density in this tiny beam makes diagnostics particularly difficult. Fluorescent screens provide maximum information but linearity and even survivability at the extremely high current densities may preclude their use. Screens consisting of aluminum-oxide powder imbedded in titanium plates, used in the present beam line, have been badly burned when a beam current of 3 Amps was used. The use of a very thin substrate to minimize energy deposition and a refractory material such as Tungsten should help but it was found that the embedding process did not work anymore. Fluorescent screen operation with Gadolinium Oxy-Sulfide has been reported at up to 10^{10} electrons/pulse at much higher energy [7], but we anticipate $\approx 10^{13}$ electrons/pulse. Recently, a very high intensity phosphor – Therbium activated Yttrium-Aluminum-Gallium-Oxide – has been obtained [8] and will be tried in the present UCSB beamline at the earliest opportunity. Phosphor bonding with Potassium-Silicate should be compatible with the high vacuum environment. Should this be found suitable, a telescopic optical system and CCD closed circuit television system (Fig. 7) will complete the system.

Even more exotic techniques such as the imaging of transition radiation or x-ray imaging from a tungsten foil may be tried if necessary.

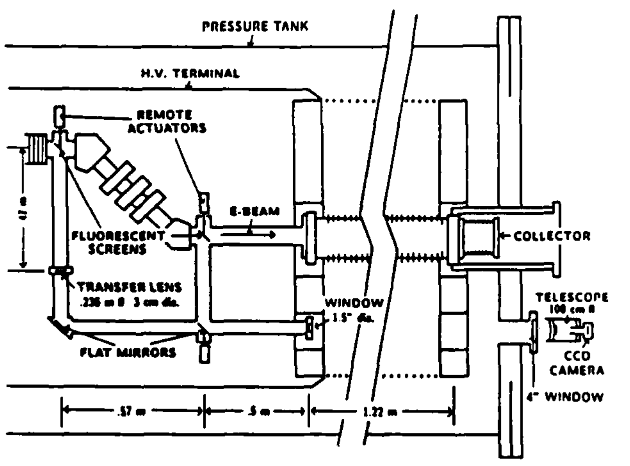

Fig. 7 Fluorescent screen beam diagnostic system

RESONATOR

Fig. 8 is a conceptual drawing of the resonator assembly. Radiation, reflected between two cylindrical resonator mirrors, is confined between two gold plated stainless steel plates of 10 mill thickness. Above and below these plates are the microundulator magnet assemblies which are, in turn, surrounded by vacuum

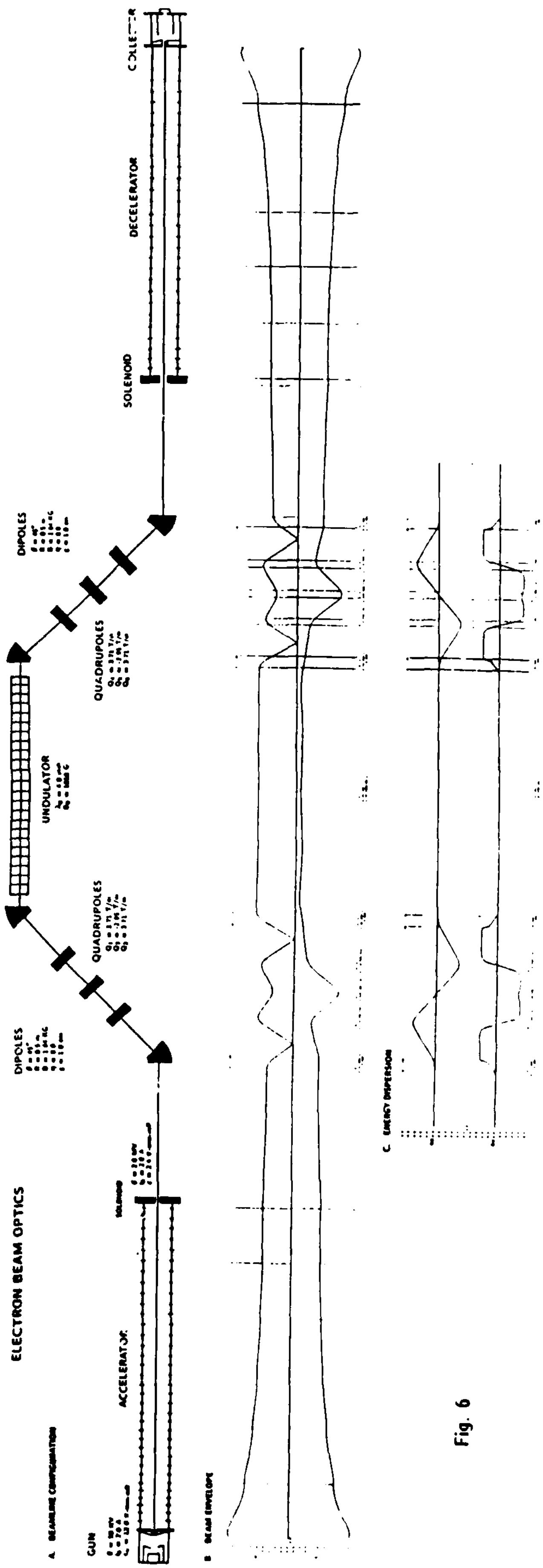

Fig. 6

chamber walls. The adjustment screws as well as the side and end plates will require o-ring seals and the sintered magnetic material will be included inside, resulting in a relatively dirty environment. Isolation from the rest of the system will be achieved by differential pumping with the electron beam passing the through small low conductance holes.

As with most FIR lasers, a waveguide configuration is dictated by the rapid diffraction of optical radiation at long wavelength – $\theta_d \approx \lambda/d$. This was the case with the present UCSB FEL and is even more imperative in the compact FEL where optical mode cross section may be only a factor of five greater than the wavelength. A novel low loss waveguide resonator was developed for the present UCSB FEL [10] and was also chosen for the compact FEL. This design is similar to a conventional TE_{10} waveguide except that the tangential H fields along the vertical walls, which are the predominant source of loss, are forced to zero to satisfy boundary conditions imposed by cylindrical resonator mirror symmetry. Analysis has been performed [9][10] with a Hermite-Gaussian function as a solution to the Helmholtz wave equation combined with the appropriate waveguide propagation vectors. The lowest order fields follow a cosine distribution in the vertical plane and a gaussian distribution in the horizontal plane.

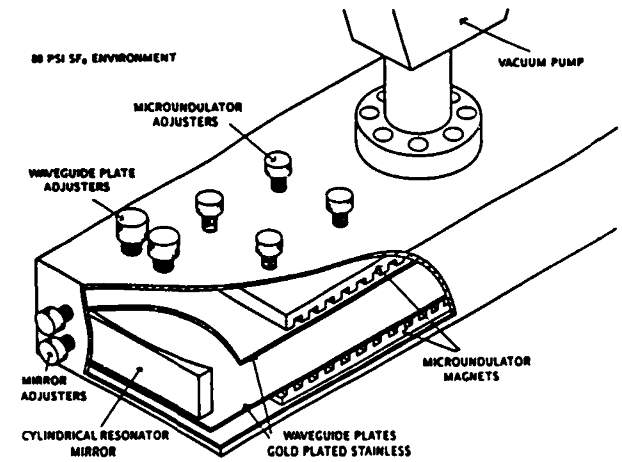

Fig. 8 Illustration of resonator and undulator system of the compact FEL

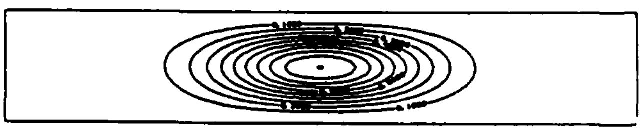

Fig. 9 Contour plot of radiation pattern at the end of the resonator

Fig. 9 is a contour plot of intensity at a mirror surface. The resultant mode frequencies are

$$\nu_{q,m,n} = \frac{c}{2L}\sqrt{\left[(q+1) + \frac{1}{\pi}(m+1)\cos^{-1}\left(1 - \frac{L}{R}\right)\right]^2 + \left[\frac{nL}{h_y}\right]^2}$$

where L=resonator length, R=mirror Radius, q=longitudinal mode index, m=horizontal transverse mode index, n= vertical transverse mode index, and h_y = resonator height. For the compact FEL parameters of Table 1, the lowest order longitudinal mode spacing (q=21956, m=0, n=1) is 157.75 MHZ, with a horizontal transverse mode spacing ($m : 0 \rightarrow 1$) of 117.6 MHZ and a vertical transverse mode spacing ($n : 1 \rightarrow 2$) of 2.431 GHZ. The FEL radiation, however, permits coupling only to modes matching the angular distribution function

$$\nu \propto \frac{1}{1 - \beta_z \cos\theta}$$

for waveguide modes of index n (m=0), $\cos\theta$ is equal to the ratio of the waveguide to free space wavevectors which results in the permitted coupling frequencies

$$\nu = \frac{\beta_z c}{\lambda_0(1 - \beta_z^2)}\left[1 + \sqrt{1 - (1 - \beta_z^2)\left(1 + \left(\frac{n\pi}{h_y}\right)^2\right)}\right]$$

where β_z is the axial component of relativistic electron velocity and λ_0 is the undulator period. For the conditions of Table 1, there are four permitted frequencies – 3.465 THZ, 3.346 THZ, 3.125 THZ, and 2.732 THZ. A more sophisticated analysis including the effects of the horizontal Gaussian distribution is presented in reference [11].

The loss per pass is $1 - e^{-4\alpha L_r}$ where α is the real part of the waveguide propagation vector determined by surface resistivity and the integral of the tangential H_z field at the top and bottom plates

$$\alpha = \frac{\sqrt{\frac{1}{\pi\nu\mu_0\sigma}}\left(\frac{n\pi}{h_y}\right)^2}{2h\sqrt{\left(\frac{2\pi\nu}{c}\right)^2 - \left(\frac{n\pi}{h_y}\right)^2}}$$

For Table 1 parameters and σ = 8.2 x 10^6 Mho/m [12] the loss/pass is .3%.

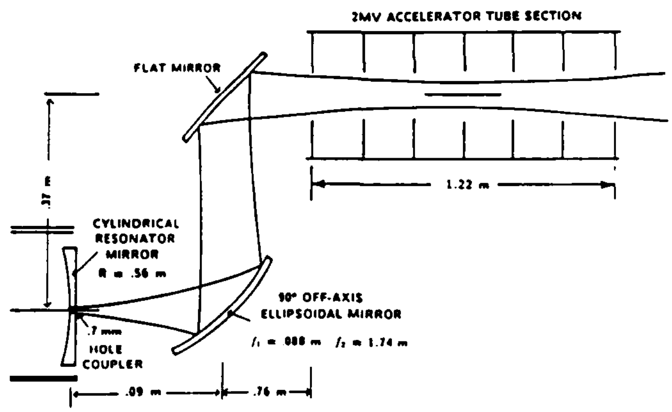

Fig. 10 Components of the optical transport system

OPTICAL COUPLING AND TRANSPORT

Fig. 10 is an illustration of the optical transport system. It should be noted that the transport of long-wavelength radiation through the high voltage environment presents certain problems. The stable maintenance of high voltage across a vacuum requires carefully graded fields and the application of ion-multiplication suppression techniques. At this point, the use of a standard NEC accelerator tube is the most conservative approach and therefore our choice. These standard tubes use 1 inch ion-loading apertures every eight inches and so provide a source of loss for a rapidly diffracting long-wavelength optical beam. In general, transmission of a gaussian beam through an aperture of radius r causes a diffraction loss of

$$l = 1 - e^{\frac{-2r^2}{w^2}}$$

where w = $1/e$ gaussian radius; and expansion of a gaussian beam

from its waist w_0 along the longitudinal axis z is governed by

$$w = \sqrt{w_0^2 + \left(\frac{\lambda z}{\pi w_0}\right)^2}.$$

The latter expression defines a maximum wavelength for transmission of a gaussian beam of maximum radius w over a distance d

$$\lambda = \frac{\pi w^2}{d}$$

while the former defines a ratio of aperture radius to beam radius for a given loss. If we arbitrarily define the loss for maximum transmission through the two end apertures as 10%, then r/w = 1.22 and

$$\lambda_{max} = \frac{\pi r^2}{1.5d}.$$

This defines a maximum wavelength of 268 μm for a 2 MV accelerator tube. If hole coupling is used, and a very small hole dimension is assumed, the radiation distribution will be the well known Fraunhofer diffraction pattern

$$I = I_0\left[\frac{2J_1(\rho)}{\rho}\right]^2 \quad , \quad \rho = \frac{2\pi r \sin\theta}{\lambda}$$

To first approximation the central lobe will diffract in a manner similar to the gaussian mode and the same approximate loss versus wavelength limits apply.

It has been recently suggested [13] that non-diffractive propagation of radiation over a finite distance is possible. A field of the form,

$$E(r,t) = e^{i(kz-\omega t)}J_0(\alpha\rho), \quad 0 < \alpha \leq \frac{\omega}{c}$$

where $\rho^2 = x^2 + y^2$ and J_0 is the zero order Bessel function of the first kind, is required. Such a pattern was generated with an annular aperture which in most cases would introduce excessive losses by itself. In the case of hole coupling from a waveguide resonator, however, losses are, to first approximation, independent of the actual shape of the hole. Application of this technique to extend the lower wavelength range of the compact FEL is under investigation.

CONCLUSION

A new generation of compact and efficient FELs appears feasible through application of "next generation" FEL concepts to those proven with the present UCSB FEL. A program to demonstrate this by construction of a compact FEL inside a 2 MV test accelerator is now underway at UCSB. Development of this machine will require the solution of many problems not previously addressed in FEL development work. None of these appear insurmountable and many solutions have already been identified. The machine will serve as a prototype of future machines as well as providing the UCSB users' facility with a valuable second source of radiation.

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